Generating a Synthetic Axion Signal for Cold Cark Matter Axion Searches Using Microwave Cavities

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1. Introduction

The process in Fig. 1 represents an axion converting into a photon in the presence of a magnetic field.

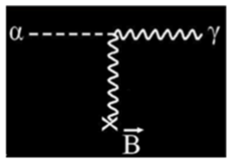

Fig. 1

In cold dark matter axion searches, microwave cavities can be used as axion detectors by making them resonate to the frequency of this final photon. If the signal created in the resonator by this process can be synthesized, it can be used for cavity calibration, and for tests of the receiver chain in axion experiments. Similarly to the converted photon, the injected RF signal is required to have a linewidth in the order of one part in 10^6, with a profile reflecting the axion kinetic energy distribution. This distribution, not known a priori, is model dependent.

In this initial work we are not concerned with a line shape reflecting a specific axion kinetic energy distribution, rather we focus on the synthesis of a signal having an exponential raise to some maximum amplitude and, likewise, an exponential fall. The most important requirement, for now, is that its 3 dB bandwidth can be dialed as needed to represent the linewidth of an axion decay in the microwave region. With this in mind, a signal emulating the RF burst from an axion to photon conversion was synthesized using commercial equipment. The signal was then injected into a resonator whose response was observed with a spectrum analyzer. This emulated axion signal, to which we may loosely refer here as *axion signal*, will be later refined and customized to reflect a specific axion line shape.

The ultimate goal of this test setup is the optimization of the receiver technology, for axion like signals, and testing of signal recovery methods, for instance matched filters, in order to extract, from the noise, candidate axion signals with an assumed line shape. In a cavity tuned to a chosen frequency, these signals would randomly appear within the resonance bandwidth of the cavity.

2. Experimental Setup

To create the RF burst, a trapezoidal waveform from a pulse generator was superimposed to an AM modulation of a carrier frequency corresponding to the axion mass. This combination generated an exponential profile centered at the carrier frequency.

We point out that this demonstration does not provide a perfectly “clean” axion signal, due to the limitations of the apparatus. For instance we realized that the internal modulator of the signal generator may not be able to completely extinguish the modulated wave, as it should be, within the time width of the external pulser. Although this issue will not be relevant when the signal is attenuated below the noise floor in simulation experiments, in the current setup it introduces undesired spectral components. Additional conditioning could be required in order to better control the features of the axion signal. Nevertheless, this demonstration clearly shows how an axion signal can be synthesized.

Once such a signal is available, it can be properly attenuated and randomized to mimic axion events in the cavity.

For convenience, the pulser was used in continuous mode in the current setup. Its frequency is not critical, as long as it is low enough to allow the cavity resonance to decay completely before the next excitation. Considering the cavity finesse, this external pulse frequency was set to 1 KHZ.

After setup, the modulated signal was fed to e weakly coupled port of a CAST-CAPP rectangular cavity kept at ~6.7 K in a cryocooler. At this temperature the cavity fundamental frequency was ~ 6.1 GHz, and its 3dB bandwidth was ~210 KHz. An axion signal at this frequency would have an intrinsic bandwidth of about 6 KHz.

In the time domain, the cavity "ringing" would therefore last for a little under 5 μs, in response to a sharp excitation at this resonant frequency. The very narrow-band axion signal, compared to the cavity bandwidth, would keep filling the cavity for about 170 μs. At the end of this excitation the cavity would decay with a characteristic time corresponding to its intrinsic Q, about 5 μs.

The cavity response was observed in a spectrum analyzer in FFT mode through a second, weakly coupled port. The SA auto calibration mode, which is a default characteristic of this model, needed to be manually turned off from the appropriate menu of the measurement settings. An oscilloscope monitored the trapezoidal digital pulse, whose independently adjustable leading edge, trail edge, and duration determined and controlled the raise time, width, and decay time of this axion signal.

While the spectrum analyzer was triggered by the leading edge of the pulse generator, the signal generator and SA were synchronized, both to prevent phase jittering, and to be able to control the frequency offset between them.

Following is a list of the instrumentation used in this work:

1. Pulse function arbitrary Generator. Keysight 81150A, 120 MHz.
2. PSG Analog Signal Generator. Keysight E8257D, 250 KHz - 20 GHz.
3. Oscilloscope. Tektronix MDO3054 Mixed Domain Oscilloscope, 500 MHz, 2.5 GS/s
4. Signal Analyzer. Keysight PXA, N9030B, 3 Hz, 8.4 GHz.
5. Network Analyzer. Keysight PNA N5222A, 3 MHz – 26.5 GHz.

In the reminder of this document we may refer to the pulse generator as PFAG, to the analog signal generator as SG, to the signal analyzer as SA, and to the network analyzer as NA. A schematic of the setup is given in Fig. 2.

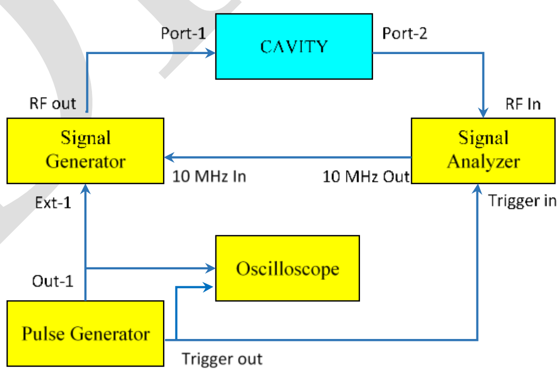

Fig. 2 – Schematic of the synthetic axion signal instrumentation and production

The frequency properties of the axion signal are mostly set through the SG, while its time characteristics are mostly determined by the pulse generator.

As stated before, the carrier frequency of the SG was selected to the chosen resonant mode of the cavity. Its amplitude was set to -20.00 dBm. The modulation source was external and the amplitude modulation (AM) type, in the SG, was exponential. Two other parameters of the SG settings are the external coupling of this instrument, set to DC, and the Automatic Level Control, which was turned off.

The PFAG output was sent to the external input of the modulator (EXT 1 Input on the SG). If we want the cavity to respond “naturally” to an axion signal, i.e. without being forced by the input signal, the pulser must be properly set. A sharp trail edge, compared to the cavity time constant, allows the cavity to show its intrinsic decay constant, while a slow (> 5 μs) raise time of the pulse entirely drives the cavity filling time. This instrument was operated in continuous mode, and its “Trigger Out 1” output was sent to the external trigger input of the Signal Analyzer (SA).

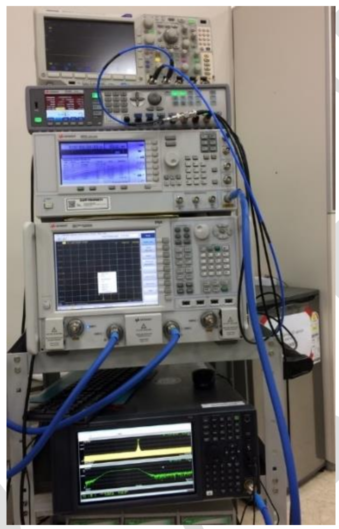

Fig. 3 - The axion signal setup

Fig. 4 gives an example of the direct observation of an axion signal with the spectrum analyzer, before injection into the cavity.

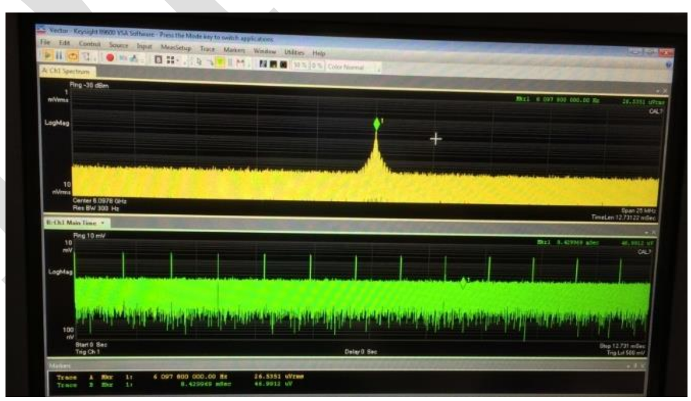

Fig. 4 – An example synthetic axion signal before injection in the cavity, observed in the spectrum analyzer. No attenuation is introduced after production with the modulator.

The FFT of the axion signal is visible in the top panel of the figure, while its time characteristics, shown in the bottom part, reflect its envelope, i.e. the input pulse to the modulator. While many Fourier components are observed on a broad band, its spectrum near the 3 dB level is fairly clean. Unfortunately a record of the spectrum at the 3 dB bandwidth was not preserved for this case. This record was instead preserved as cavity response, seen in Fig. 6.

Fig. 5 – A particular setting of the pulser

In response to an AM modulated pulse width of 50 μs, a "20 KHz axion width", as shown in Fig. 5, the cavity spectrum has a 3dB level of 20 KHz, and its time domain profile shows the same width, 50 μs, as the modulating pulse. The 10 μs leading and falling edges, force the cavity to raise and fall to and from its maximum amplitude response, respectively, with the same time span.

Fig 6 – The signal Analyzer representation in FFT mode of a "20 KHz axion signal width". Frequency domain on the top panel, time domain on the bottom panel.

The full scale of the time domain in Fig. 6 is 100 μs.

Fig. 8 corresponds to the pulse settings of Fig. 7, lead edge and trail edge 10 ns, "axion width" 20 μs. The full scale in the time domain part of the spectrum is 50 μs. The sharp fall of the trail edge lets the cavity decay naturally with its characteristic time, whereas the leading edge forces the cavity to raise more rapidly than its intrinsic time.

Fig 7 – Top: the monitoring oscilloscope.

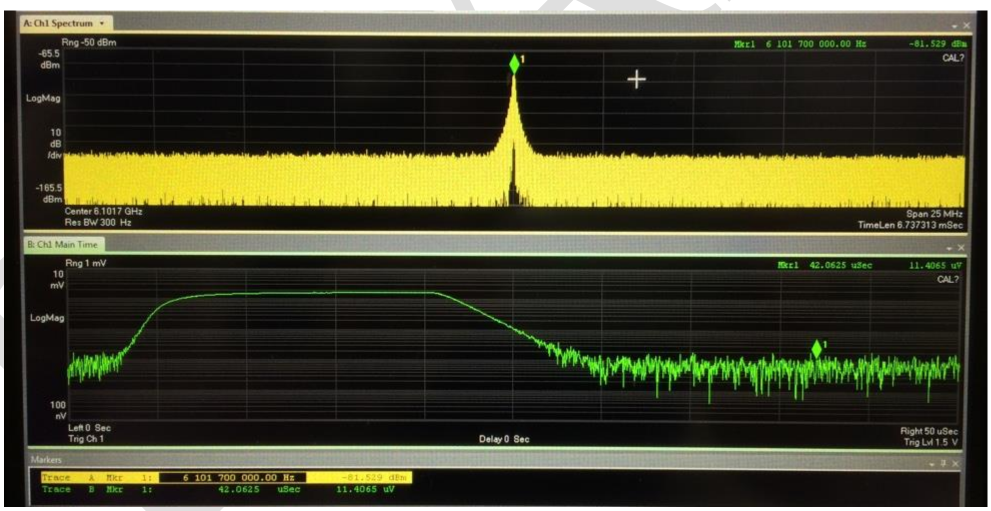

Fig. 8 – The cavity response to a 20 μs "axion width"

3. Conclusion

We demonstrated that an axion signal in a RF resonator can be synthesized and controlled with commercially available instrumentation. Although this signal needs refinements, it can be customized to the needs of a specific cold dark matter axion search experiment. Since the modulator in the setup has arbitrary function generator capabilities, this apparatus is already capable to produce the necessary refinements, for instance a maxwellian line shape.